

# Phase-resolved Crab pulsar measurements from 25 to 400 GeV with the MAGIC telescopes

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**Abstract.** We report on observations of the Crab pulsar with the MAGIC telescopes. Our data were taken in both monoscopic ( $> 25$  GeV) and stereoscopic ( $> 50$  GeV) observation modes. Two peaks were detected with both modes and phase-resolved energy spectra were calculated. By comparing with Fermi-LAT measurements, we find that the energy spectrum of the Crab pulsar does not follow a power law with an exponential cutoff, but has an additional hard component, extending up to at least 400 GeV. This suggests that the emission above 25 GeV is not dominated by curvature radiation, as suggested in the standard scenarios of the OG and SG models.

## 1. Introduction

The Crab pulsar is the compact object left over after a historic supernova explosion that occurred in the year 1054 A.D. It is among the brightest known sources at GeV energies. However, despite numerous efforts, a spectral steepening made its detection above 10 GeV elusive until 2008. Consequently, the presently preferred Outer Gap (OG) [1] and Slot Gap (SG) [2] models predict the emission to be produced through curvature radiation, which implies an exponential cutoff at a few GeV. The new satellite-borne gamma-ray detector Fermi-LAT, which can measure the spectra of gamma-ray pulsars up to a few tens of GeV, became operational in August 2008. The spectra measured by Fermi-LAT can be described by a power law with an exponential cutoff, which supported the OG and the SG model.

In 2008, the MAGIC-I telescope finally detected the Crab pulsar above 25 GeV [3] with a newly implemented trigger system, the Sum Trigger [4]. Recently, the VERITAS collaboration reported pulsed gamma rays at energies exceeding 100 GeV [5]. However, the cutoff energy of the Crab pulsar spectrum determined by Fermi-LAT was still  $\sim 6$  GeV, which seemed to be in conflict with the very-high-energy data [6].

Here we present the spectral study of the Crab pulsar, using the public Fermi-LAT data and four years of MAGIC data recorded by the single telescope and the stereoscopic systems.

## 2. The MAGIC telescopes

The two MAGIC telescopes [7, 8], situated on the island of La Palma (28.8° N, 17.8° W, 2220 m a.s.l.), use the Imaging Atmospheric Cherenkov Technique to detect gamma rays above a few tens of GeV<sup>1</sup>. During its monoscopic data taking era, a low-energy trigger system called Sum Trigger was developed and implemented in MAGIC-I in order to search for gamma-ray pulsars. It reduced the monoscopic energy threshold down to 25 GeV.

Since MAGIC started operating in stereoscopic mode in summer 2009, its background suppression was substantially improved and a sensitivity<sup>2</sup> of 0.8% Crab nebula units above 250 GeV has been achieved [9]. Since for technical reasons, the Sum Trigger cannot participate in the stereo trigger, MAGIC has two independent observation modes for pulsars: Monoscopic, with lower threshold, and stereoscopic, with lower systematics and better sensitivity.

## 3. Mono-mode observations

MAGIC-I observed the Crab pulsar with the Sum Trigger in the winters of 2007/08 and 2008/09. After a careful data selection, the total effective observation time was 59 hours.

The light curve of the Crab pulsar obtained with the mono-mode observations is shown in Fig. 1 (left). Following the usual convention adopted in the EGRET era [10] of  $P1_E$  [0.94 – 0.04] and  $P2_E$  [0.32 – 0.43], the numbers of excess events in  $P1_E$  and  $P2_E$  are  $6200 \pm 1400$  ( $4.3\sigma$ ) and  $11300 \pm 1500$  ( $7.4\sigma$ ). Summing up  $P1$  and  $P2$ , the excess corresponds to a significance of  $7.5\sigma$ . The background level was estimated using the phase interval [0.52 – 0.88].

Based on these excess events, the phase-resolved energy spectra of the Crab pulsar above 25 GeV were computed and are shown as yellow squares in Fig. 2. They are compatible with power laws [11]. The energy spectrum measured by Fermi-LAT is also shown in the same figure. For the Fermi-LAT points, 1 year of the Fermi-LAT data (August 2008 - August 2009) were used. The MAGIC-Mono measurements are not compatible with an extrapolated exponential cutoff spectrum as determined by Fermi-LAT. A detailed statistical analysis showed the inconsistency amounts to  $6.7\sigma$ ,  $3.0\sigma$ , and  $5.8\sigma$  for  $(P1 + P2)_E$ ,  $P1_E$  and  $P2_E$ , respectively (see [12] and [11] for more details on the monoscopic analysis).

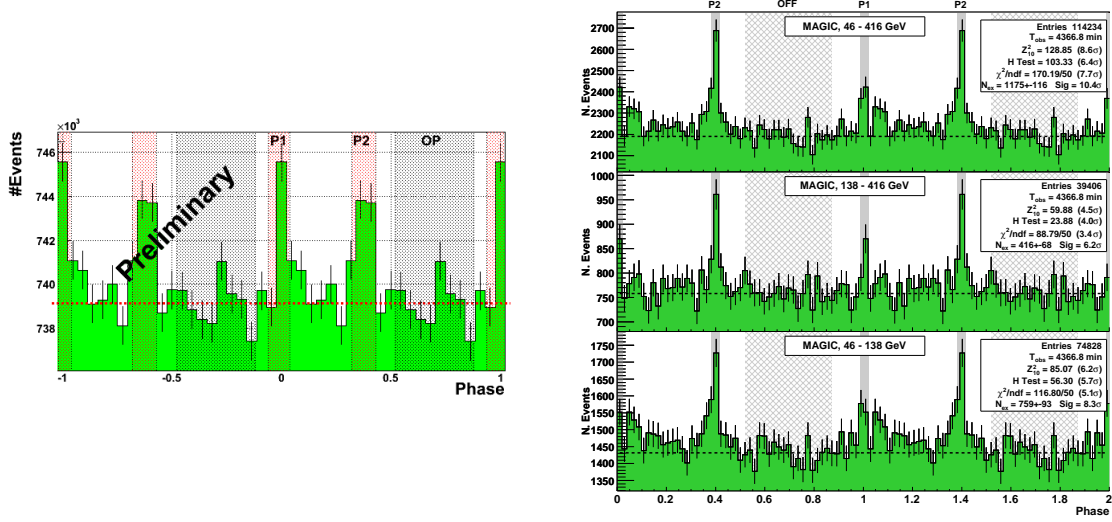
## 4. Stereo-mode observations

In stereoscopic observations, MAGIC has collected 73 hours of optimal quality Crab pulsar data between October 2009 and February 2011. The right panel of Fig. 1 shows the light curve of the Crab pulsar obtained by stereo-mode observations in the total energy range of 46 – 416 GeV, and two energy sub-bins of it. The significance of the pulsation was tested with the  $Z_{10}^2$  test, the H test [13], and a simple  $\chi^2$ -test. None of these makes an a-priori assumption concerning the position and shape of the pulsed emission, and they yield significances of  $8.6\sigma$ ,  $6.4\sigma$  and  $7.7\sigma$ , respectively. By fitting two Gaussians to the two peaks, the peak positions are estimated to be  $0.005 \pm 0.003$  and  $0.3996 \pm 0.0014$ , while the corresponding FWHMs are  $0.025 \pm 0.007$  and  $0.026 \pm 0.004$ . Defining the signal phases as  $\pm 2\sigma$  of the fitted Gaussian around the peaks, we calculate spectra both for the conventional, unbiased  $P1/2_E$  intervals (see above), and for the narrower peaks  $P1_M$  [0.983 – 0.026] and  $P2_M$  [0.377 – 0.422] that we find in our lightcurve.

The phase-resolved energy spectra are also shown in Fig. 2. They connect with the mono-mode measurements within statistical and systematic errors, and are not incompatible with a power law. Further details of the results of the stereo-mode observations are presented in [14].

<sup>1</sup> The threshold in standard trigger mode, defined as the peak of the simulated energy distribution for a Crab-nebula-like spectrum after all cuts and at low zenith angles, is 75 – 80 GeV.

<sup>2</sup> Defined as the source strength needed to achieve  $N_{\text{ex}} / \sqrt{N_{\text{bkg}}} = 5$  in 50 h effective on-time.



**Figure 1.** MAGIC folded light curves of the Crab pulsar. Left: Monoscopic light curve (2007 - 2009). Shaded areas are the on-phase regions P1/2<sub>E</sub>. Right: Stereoscopic light curve (2009 - 2011) for the total range in estimated energy, and for two sub-bins separately. The shaded areas are the on-phase regions P1<sub>M</sub> and P2<sub>M</sub> (see text), the light shaded area is the off-region [0.52 - 0.87]. The dashed line is the constant background level calculated from that off-region.

## 5. Discussion and conclusion

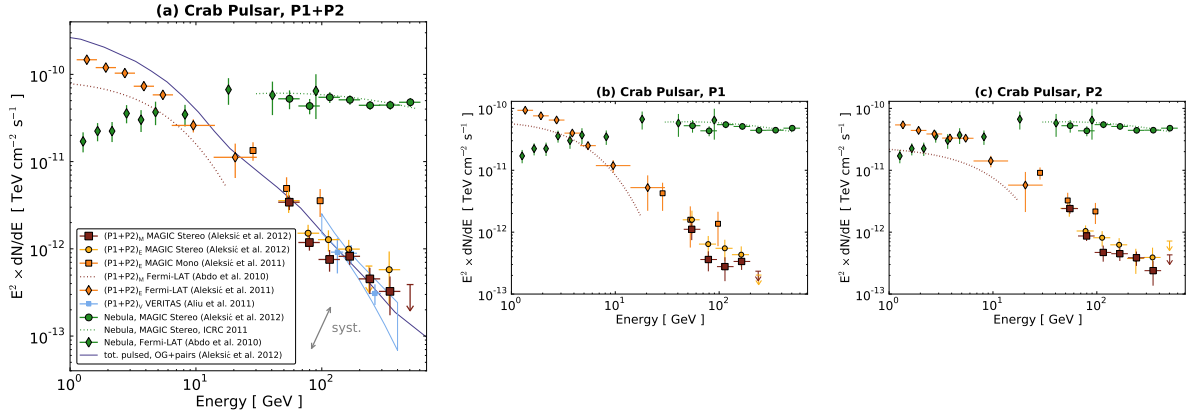
We found a pulsed VHE gamma-ray signal from the Crab pulsar in monoscopic and stereoscopic MAGIC data that allows us to present spectra with an unprecedentedly broad energy range and phase resolution. Our spectra range over more than one order of magnitude, and, along with Fermi-LAT data [6], comprise for the first time a gamma-ray spectrum of the Crab pulsar from 100 MeV to 400 GeV without any gap. On the high-energy end, they are in good agreement with recently published VERITAS spectra of P1+P2 above 100 GeV [5], including also the positions and narrow widths of the two pulses.

A possible theoretical explanation of the spectrum [11, 14] is that the spectral tails arise from inverse Compton scattering of secondary and tertiary electron pairs on magnetospheric IR-UV photons. The model predicts the onset of that component at a few tens of GeV, producing a power law spectrum that possibly extends up to TeV energies. The modeling from [14] is shown as a blueish solid line in Fig. 2(a). It is compatible with the measurements of mono- and stereoscopic MAGIC, and VERITAS. It shall be noted that the GeV flux of the model in [14] is too high to match the Fermi-LAT data because it contains bridge emission.

The two crucial spectral features to establish in order to benchmark this and other models are a possible upward-kink in the transition region between curvature and hard component, and the detection or exclusion of a terminal cutoff at a few hundred GeV. The MAGIC telescopes, which are being upgraded in 2011, can provide both of these benchmarks in the coming years, when more data will improve the statistical precision of the measurements.

## 6. Acknowledgments

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**Figure 2.** Compilation of spectral measurements of MAGIC and Fermi-LAT for the two emission peaks P1 and P2 separately, and both peaks together. The VERITAS spectrum is only available (and shown) for  $P1_V + P2_V$ , which are yet narrower than  $P1/2_M$ . For comparison, the Crab nebula measurements of MAGIC and Fermi-LAT are also shown. Points of similar color refer to the same phase intervals (marked by the indices **M**AGIC, **E**GRETT, **V**ERITAS, see text). The MAGIC flux points are bias-corrected using an unfolding technique [15]. The blueish solid line is the modelling discussed in Section 5.

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